Distributed Automated Medical Robotics to Improve Medical Field Operations

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ABSTRACT

Combat casualty and en-route care could be improved through immediate expert medical assessment and treatment. New approaches in the delivery of medical care have the potential to decouple the need for deployment of highly trained medical professionals with each advanced unit and the ability to provide sophisticated medical and surgical expertise on demand. The U.S. Army Telemedicine and Advanced Technology Research Center (TATRC) is currently sponsoring several medical robotic efforts that could augment care provided by the combat medic. This article will provide an overview of key teleoperated and automated robotic technologies being developed by TATRC that could improve combat casualty care.

1.0 INTRODUCTION

Current medical technology provides limited help to the combat medic. Enemy fire, multiple casualties, and limited experience often delay treatment of life-threatening conditions. Non-medical teleoperated and autonomous robotic systems are proven military force multipliers that could be leveraged in medical field operations to deliver expert care when and where it is needed. These technologies could permit remote medical teams to diagnose and treat casualties as well as manage time-critical medical resources in a highly efficient manner. The work described herein is a first step toward realizing the long-term goal of a suite of rugged, remotely operated medical robotic systems that could significantly improve combat casualty and en-route care.

Military robotic combat casualty care has three primary goals: safely extracting patients from harm's way; rapidly diagnosing life threatening injuries such as non-compressible hemorrhage, tension pneumothorax and loss of airway; and delivering life-saving interventions. Morbidity statistics indicate that 86% of all battlefield mortality occurs within the first 30 minutes of trauma. Teleoperated and autonomous surgical robots can deliver expert surgical care within the "golden hour" on the battlefield as well as during transport to military treatment facilities. Moreover, medical robots must robustly operate in extreme environments and provide effective combat casualty care as close as possible to the point and time of injury.

Several "proof-of-concept" projects have demonstrated the feasibility of remote robotic diagnosis and treatment of casualties. The U.S. Army has also launched several physiological sensor and image-based robotic casualty assessment and triage research projects to relay vital sign information such as skin temperature, pulse, and blood pressure. However, these capabilities are currently only experimental and are non-ruggedized, teleoperated component capabilities at best. Visual examination information is planar, and often lack depth and full five-sense information (e.g., tactile feedback).

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14. ABSTRACT
Combat casualty and en-route care could be improved through immediate expert medical assessment and treatment. New approaches in the delivery of medical care have the potential to decouple the need for deployment of highly trained medical professionals with each advanced unit and the ability to provide sophisticated medical and surgical expertise on demand. The U.S. Army Telemedicine and Advanced Technology Research Center (TATRC) is currently sponsoring several medical robotic efforts that could augment care provided by the combat medic. This article will provide an overview of key teleoperated and automated robotic technologies being developed by TATRC that could improve combat casualty care.

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Military-funded research has demonstrated that surgical robotic systems can be used to perform robotic telesurgery, successfully deployed to extreme environments, and wirelessly operated via microwave and satellite platforms. However, addressing acute and life threatening injuries, such as major non-compressible vascular injury, requires development of new field deployable surgical robots that move beyond stereoscopic, bimanual telemanipulators. Moreover, they should leverage advances such as autonomous imaging analysis and application of directed energy technologies already used in non-medical military robotic systems. Additional research is also required to overcome the operational communication challenges of limited bandwidth, latency, and loss of signal in the deployed combat environment.

Multiple investigators funded by the US Army Medical Research and Material Command (MRMC) are developing teleoperated and autonomous robotic systems that could perform several basic – but critical – life saving procedures. In particular, TATRC is directing research in several areas such as autonomous airway control, laser tissue welding, and automated anesthesia. Several of these projects will be reviewed as well as how these systems could be integrated into casualty care platforms currently under development.

2.0 CASUALTY CARE LIFE SUPPORT PLATFORMS

The Life Support for Trauma and Transport or "L-STAT" was a DARPA funded program to develop a portable intensive care unit (ICU) that would provide life support, physiological monitoring, telemedicine, and autonomous interventions during transport. L-STAT was capable of providing up to two hours of life support and includes a ventilator with on-board oxygen, fluid/drug infusion, suction, defibrillator, blood chemistry analysis, and patient physiological monitoring. The original version of L-STAT was cumbersome and heavy, severely limiting its utility. The L-STAT subsequently evolved into the L-STAT Lite and Med-Ex 1000. The MedEx-1000 weighs less than 40 pounds and can be used independently of a litter. The Med-Ex 1000 was developed and released for sale in 2009. Current versions of the L-STAT, Monitoring Oxygen Ventilation and External Suction (MOVES) device, and the Lightweight Trauma Module (LTM) are being evaluated by the US military for future use in en-route care.

The addition of bioinformatics, wireless data communication, additional imaging capabilities, robotic manipulators, and increased mobility would move these platforms toward the goal of an autonomous field deployable surgical platform. Next generation platforms may include diagnostic enhancements such as portable ultrasound, digital X-ray, and telediagnosis via remote controlled camera. Prospective therapeutic additions explored within TATRC research include serpentine robotic manipulators for performing intubation, High Intensity Focused Ultrasound for treating hemorrhage, robotic laser tissue welding, and target controlled infusion anesthesia systems.

3.0 TRAUMA ASSESSMENT AND INTERVENTION

The U.S. military is continually developing new diagnostic and therapeutic modalities to improve care of injured warfighters. Some of the more promising technologies that could readily be incorporated into medical robotic systems are high intensity focused ultrasound (HIFU), laser tissue welding, autonomous airway management, and target controlled infusion anesthesia (TCIA). This section will review these and several other technologies currently under development.

3.1 High Intensity Focused Ultrasound (HIFU)

The potential of using non-invasive methods for hemorrhage control is critical in combat scenarios where immediate access to surgery is impossible. It has been demonstrated that HIFU can seal vascular injuries of

up to 3mm in diameter and the technology is evolving rapidly. A DARPA-funded project, "Deep Bleeder Acoustic Coagulation" (DBAC), has produced a prototype HIFU device that could be applied in a combat situation by minimally trained operators to automatically detect the location and severity of bleeding and coagulate the bleeding vessel (Figure 1). Doppler based automated hemorrhage detection algorithms are coupled with volumetric data to localize the bleeding source. HIFU delivery and dosing for safe acoustic hemostasis raises tissue temperature to a range of 70-95ºC in an operationally relevant 30-second timeframe.

Energid Technologies, Inc. has prototyped a telepresence-based robotic HIFU system that could allow a trauma surgeon or a trained operator to remotely control bleeding in a wounded soldier in the field (Figure 2). Their system implements a series-elastic actuator for arm flexibility, new methods of detecting and controlling hemorrhage through HIFU, and an intuitive human interface. The system is robust and stable even in the presence of data latency and bandwidth constraints.

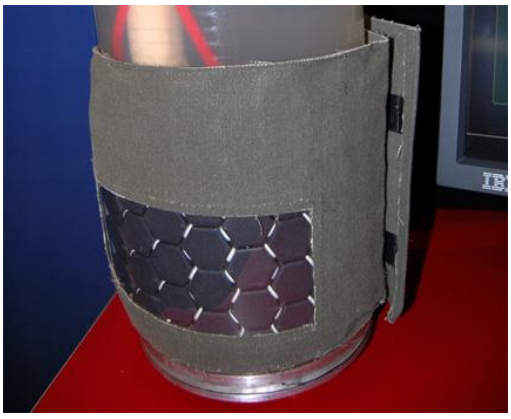

Figure 1: DBAC powered cuff.

Figure 2: Animation of Energid HIFU system.

3.2 Robotic Laser Tissue Welding

SRI International, Inc (SRI) is investigating robotic-assisted laser tissue welding as a means to circumvent the need for suturing (Figure 3). Telerobotic suturing is especially challenging at longer latencies which would be encountered during robotic combat casualty care. These TATRC funded experiments used a robot to uniformly deliver laser energy to close a laceration (Figure 4). Two methods were demonstrated for direct tissue welding: bovine serum albumin / hyaluronate acid solders and chitosan films. Robot-controlled tissue welding of lacerations in explanted pig eyes decreased the total time of tissue apposition from a manual suturing from approximately eight minutes to three minutes. Laser welded tissue had similar burst pressure as manually sutured tissue. These experiments demonstrated that robotic laser tissue welding has potential value and further research is indicated.

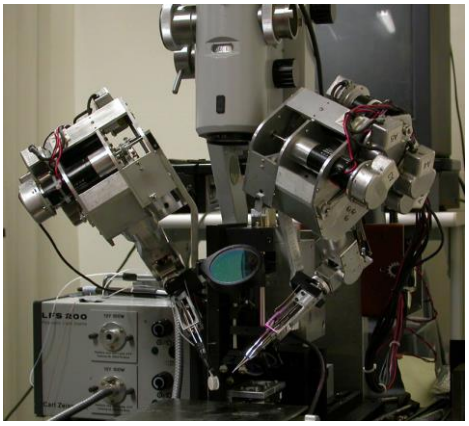

Figure 3: SRI Robotic's laser tissue welder.

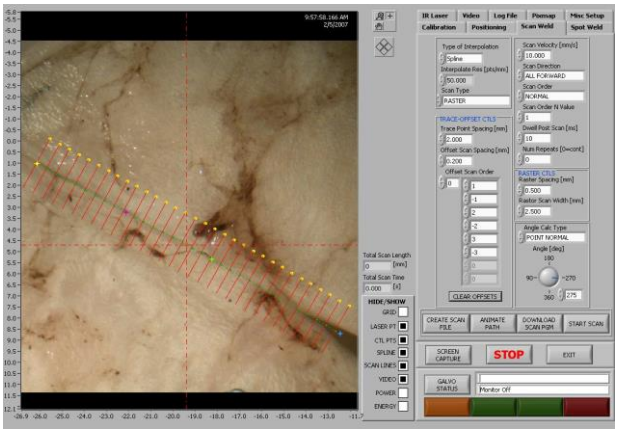

Figure 4: Laceration closed using tissue welder.

3.3 Autonomous Airway Management

Controlling the airway is the one of the most critical tasks that must be performed by casualty first responders. Energid Technologies, Inc. is developing an ultra-lightweight, portable, rugged, mechatronic device capable of performing autonomous and semi-autonomous (assistive) endotracheal intubation (ETI). The device is a battery powered, self-contained handheld unit capable of safely delivering an endotracheal tube into a patient's airway in less than 30 seconds. To ensure portability, the device will have the approximate dimensions and weight of a beverage bottle. Energid's proprietary machine vision algorithms are used to direct a novel, flexible manipulator inside the patient's airway. The system subcomponents can themselves be used as assistive technologies both for ETI vision feedback and manual ETI. The device will be capable of performing at least 10 intubations on a single battery charge. In the upcoming two years, the system will be tested in an instrumented airway phantom, and through animal and human cadaveric studies in collaboration with anesthesiologists and trauma surgeons at the Massachusetts General Hospital (MGH).

Figures 5 and 6 show the design of a two-stage flexible tube assembly mounted on a deployment unit. The deployment unit controls the tangential motion of each tube stage independently through lead screws. Three linear actuators control the tip orientation of each stage. In addition each tube tip is outfitted with an inflatable tip similar to the ones found in standard endotracheal tubes. Once positioned, the inner tube will be left behind as the endotracheal tube. The tube dimensions and material properties will be similar to standard endotracheal tubes currently used.

Figure 5: Energid intubation device.

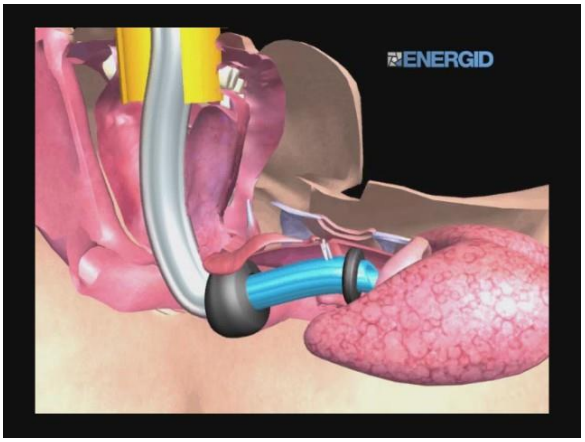

Figure 6: Simulated robotic intubation.

3.4 Target Controlled Infusion Anesthesia (TCIA)

The development of closed-loop target controlled infusion anesthesia (TCIA) systems has important implications in trauma care. Many sedatives and anesthetics have narrow therapeutic windows and the lack of a sensor that can accurately measure serum levels has been a regulatory hurdle which has limited application of TCIA in the United States (Figure 7). The integration of closed-loop anesthesia systems throughout roles of care would greatly facilitate the management of casualties, and TCIA could have a significant impact on both military and non-military healthcare.

The University of Tennessee is currently developing an electrochemical biosensor that permits rapid and accurate measurement of blood levels of the anesthetic propofol. The performance of prototype electrochemical biosensor designs are being evaluated for real time quantification of propofol in complex solutions. The sensors will also be used to assess concentrations of DIPP in blood and gas. In addition, the effects of biofouling on signal integrity in blood and assessment of performance in artificial and living systems will be determined. Organic membrane coated gold electrodes and multiple, redundant 3-wire voltametric Carbon Nano Forest (CNF)-based electrochemical cells will be tested. Figure 8 contains an image of an early prototype CNF microelectrode sensor.

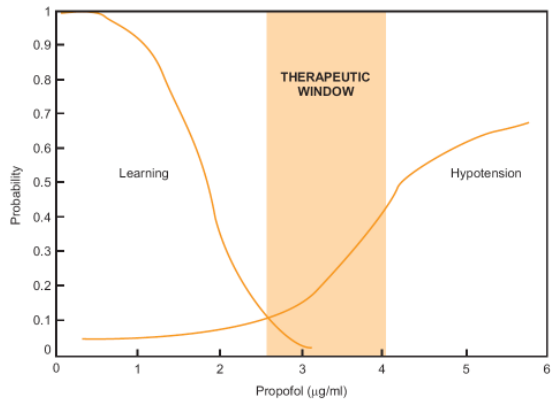

Figure 7: Narrow therapeutic window for propofol.

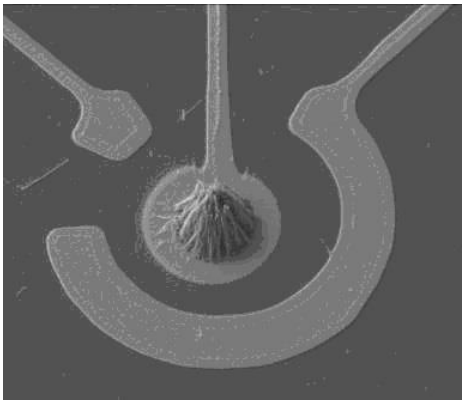

Figure 8: UT Carbon Nano Forest microelectrode.

4.0 ROBOT PATIENT INTERFACE

Robotic trauma diagnosis and intervention is performed using instruments and tools mounted on the end of a robotic manipulator. In addition to using an open approach, robots could also deliver trauma and en-route care via percutaneous and transcutaneous approaches.

4.1 Percutaneous and Transcutaneous Intervention

Robotic manipulators used for percutaneous and transcutaneous assessment and care will require end-effectors with the ability to safely interact with the patient as well as adapt to various surface irregularities. Ultrasound remains a promising technology for use on the battlefield. High-resolution ultrasound imaging has been demonstrated to be capable of detecting internal bleeding and bone fractures. In addition, an ultrasonic welding device is now being applied as an alternative to manual suturing. As previously discussed, HIFU can be used to stop bleeding relatively quickly.

In transcutaneous imaging and therapy, it is typically required that a specified level of force be applied on the patient, which is made particularly challenging due to the compliance of soft tissue and patient movement. It is extremely difficult for a manipulator to respond quickly enough to accommodate for motion due to high inertia and inaccuracies caused by low stiffness at the tool point. Ultrasonic probes have been mounted and demonstrated on parallel manipulator devices, but the range of motion is very limited. Alternatively, serial-parallel robot architectures can be implemented in which the serial robot moves the probe within close proximity of the patient, while a parallel mechanism end-effector maintains constant force contact of the probe using minute adjustments. In addition to providing increased accuracy and bandwidth, a new robotic end-effector mechanism could also yield increase the level of safety through active compliance.

The best system for achieving active compliance would be to combine the gross positioning capability of a serial link manipulator with the fast response of parallel end-effector mechanism. TATRC currently has an active SBIR program to develop a six degree of freedom (6-DOF) parallel end-effector mechanism that can be mounted on the end of a medium-sized robot manipulator for compliance-based medical imaging and surgical interventions. The goal of this program is to build a prototype and implement a controller that can achieve active compliance of less than 2 N/cm at up to 10 Hz bandwidth. This system will be demonstrated on a serial-link manipulator and will be compatible with field use.

5.0 OPERATION UNDER EXTREME CONDITIONS

As previously discussed, DARPA funded SRI to develop a telesurgery system that would allow a remote surgeon to treat an injured soldier on the battlefield. The technology developed in this program was licensed to Intuitive Surgical, Inc and subsequently morphed into the daVinci surgical system. The daVinci has been widely applied in minimally invasive surgery. Currently, over 1000 daVinci systems are used worldwide and 200,000 operations are performed annually. However, this minimally invasive robotic surgery system cannot be used in an operationally and clinically relevant manner for battlefield or en route combat casualty care. The current version of the da Vinci is too large and bulky for deployed use. Furthermore, it is ill suited for trauma surgery which requires rapid open exposure and gross manipulations of tissues to identify and manually treat injuries (e.g., abdominal packing, tissue mobilization, retraction, etc).

Due to the extreme nature of battlefield environments, the next generation mobile surgical robots will be smaller, robust trauma focused systems that leverage non-medical military telecommunication, computing, imaging, and mechanical resources. TATRC funded telesurgery research has used a variety of robotic surgical

platforms to explore telerobotic surgery in extreme environments. These systems include: the University of Washington RAVEN and the SRI M7.

The RAVEN is a small deployable surgical robot being developed at the University of Washington BioRobotics Laboratory with support from multiple government agencies including the U.S. Army. The system consists of a slave component that resides with the patient and a master controller permitting remote control of the slave by the surgeon. The master site has a surgeon console that currently employs dual PHANToM Omni devices to control two surgical manipulators/instruments, a foot pedal, and a video screen displaying images from the surgical site. The video and robot control are transmitted using standard Internet communication protocols. The user interface uses open source commercial off the shelf technology and therefore it is remarkably low cost, portable, and interoperable (i.e., it can readily control other systems with limited modifications).

SRI's M7 surgical robot was initially developed in 1998 with funding from the U.S. Army. The M7 leveraged military funded development of SRI's original telepresence surgical system. The features of this robot include a large workspace accessible via two anthropomorphic robotic arms with seven force-reflective degrees of freedom. These robotic arms manipulate conventional "open" surgical instruments allowing for complex surgical tasks to be performed. The system was recently upgraded with high definition stereoscopic vision, ergonomic hand controllers, and limited automation. Both of these surgical robotic systems have been utilized in extreme environments to evaluate feasibility as well as guide future research and development.

Collaborative telesurgery research was conducted within the NASA Extreme Environment Mission Operations (NEEMO) program in collaboration with the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), the Centre for Minimal Access Surgery (CMAS), the Canadian Space Agency, and US Army TATRC. NEEMO missions occur within the NOAA National Undersea Research Center Aquarius habitat located at 19 meters depth within the Florida Keys. In 2006, NEEMO 9 explored the use of telementoring, and telerobotic surgery to provide emergency diagnostic and surgical capabilities in an extreme environment. Mission accomplishments included: the first successful deployment and use of a surgical robot (SRI's M7) in an extreme environment and the use of microwave wireless telecommunications in support of telesurgery (Figure 9).

Simulated surgical procedures were performed to evaluate the effect of increasing latency on surgeon performance. Latency of over 500 msec was found to greatly impact performance. While the remote surgeon was able to suture simulated tissue despite 2 sec latency, placing and tying a single suture in 10 minutes is not clinically relevant. These experiments demonstrated that latency compensation up to approximately 500 msec was possible by modifying surgical technique to include slow, one-handed movements. Several technologic solutions were successfully used to overcome sub-second latency such as motion scaling. These M7 telesurgical experiments suggested further research in automation was necessary. Astronauts on NEEMO 9 also evaluated the University of Nebraska – Lincoln (UNL) in vivo robots. These novel miniature mobile robots were deployed inside a laparoscopic simulator and found to improve visualization of the surgical field.

In 2007, NEEMO 12 primarily focused on evaluation of image guided, supervisory controlled autonomous function to overcome latency. A modified M7 was used to perform an ultrasound guided, semi-autonomous needle insertion into a simulated blood vessel The RAVEN surgical robot was also deployed and the modified SAGES (Society of American Gastrointestinal and Endoscopic Surgeons) Fundamentals of Laparoscopic Surgery (FLS) protocol was used to objectively assess telesurgical performance. In separate experiments, the RAVEN was combined with a small unmanned aerial vehicle (UAV)-based communications platform to remotely perform proof of concept surgical tasks in the high desert (Figure 10). Finally, the M7 was modified

via acceleration compensation and assessed during parabolic flight for possible future use during critical care air transport.

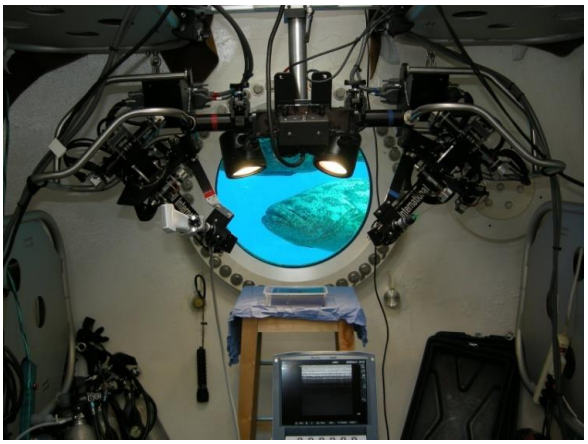

Figure 9: SRI M7 deployed undersea in Aquarius.

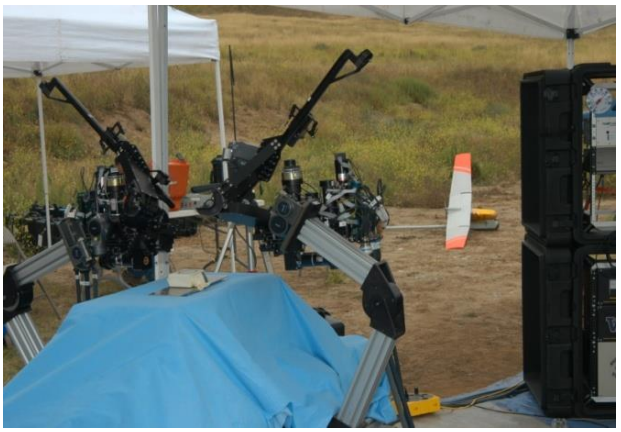

Figure 10: Raven/AeroVironment UAV in high desert.

5.1 Telerobotic and Automated Robotic Surgery

Trauma Pod (TP) was a DARPA program to develop a semi-autonomous telerobotic surgical system that could be rapidly deployed and provide critical diagnostic and life-saving interventions in the field. The footprint was 8ft x 18ft so that it could to fit within an International Standards Organization (ISO) shipment container for ready deployment. The Phase I proof of concept platform was comprised of a daVinci Classic surgical robot supported by an automated suite of commercially available and custom designed robots. The surgeon remotely controlled the robotic suite to perform representative tasks that included placing a shunt in a simulated blood vessel and performing a bowel anastamosis.

While the daVinci robot is not a readily deployable system, the Phase 1 effort proved that a single operator could effectively teleoperate a surgical robot and integrated suite of automated support robots to perform relevant surgical procedures on a simulated patient. For example, the Scrub Nurse Subsystem (SNS) system, developed by Oak Ridge National Laboratory, automatically delivered instruments and supplies to the surgical robot within 10 sec (typically faster than a human). The Tool Rack System (TRS), developed by the University of Washington, held, accepted, and dispensed each of fourteen surgical tools. The Supply Dispensing System (SDS), developed by General Dynamic Robotic Systems, provided sterile storage, delivery and tracking of standard surgical supplies. The Supervisory Controller System SCS, developed by University of Texas, provided high-level control of all automated subsystems involved in supply dispensing / tool changing and coordinated these functions with the surgical robot. The Patient Imaging (GE Research) utilized the L-STAT platform to embed CT like capabilities as well as 2-D fluoroscopic data. The User Interface System (UIS) developed by SRI International provided a visual, verbal, aural, and gesture-based interface between the surgeon and TP system. The visual display consisted of a stereoscopic view of the surgical site augmented by physiologic data, icons and other supporting information.

Results from the Phase I demonstration in 2007 shown in Figure 11 include:

- Automatic storing and dispensing of surgical tools by the TRS with 100% accuracy

- Automatic storing, de-packaging dispensing and counting supplies by the SDS
- Automatic change of surgical tools and delivery and removal of supplies by SNS
- Speech-based interface between a tele-operating surgeon and the system through the UIS
- Automatic coordination and interaction between system components such as the SRS and SNS
- Performing iliac shunt and bowel anastamosis procedures on a phantom by a tele-operated SRS

Future programs will develop a single robot designed to rapidly diagnose and innovatively treat life-threatening battlefield injuries via automated ATLS procedures and damage control surgery.

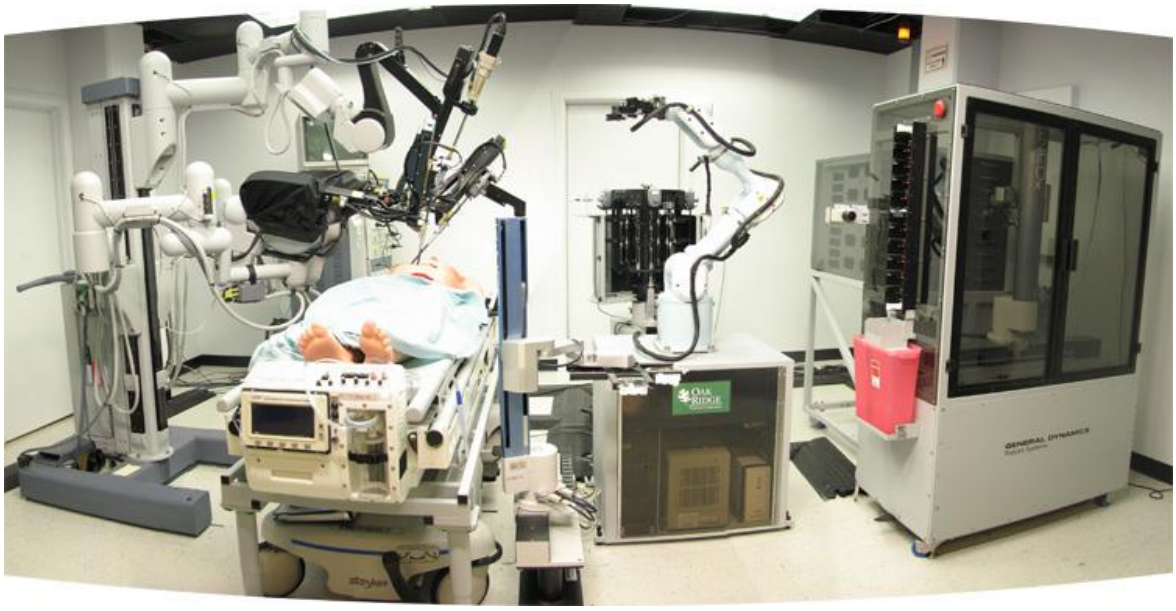

Figure 11: Phase I DARPA Trauma Pod Demonstration.

6.0 CONCLUSION

The technological revolution of the past three decades is catalyzing a paradigm shift in the care of battlefield casualties. Telecommunications and robotic technology can revolutionize battlefield care by safely extracting patients from harm's way, rapidly diagnosing life threatening injuries, and delivering life-saving interventions. Telecommunication and robotic limitations that prevent robust intervention at a distance are areas of continued military research and development. As these limitations are overcome, medical robots will provide robust casualty extraction and care that will save the lives and limbs of our deployed warfighters. New approaches for delivering medical care have the potential to decouple the need for deployment of highly trained medical professionals with each advanced unit and the ability to provide sophisticated medical and surgical expertise on demand. TATRC continues to push development of distributed, autonomous medical technology that advances field medical operations and will save the lives and limbs of our warfighters.

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